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G1F
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(54) **A device**

(57) A sensor 1 for an inclination measuring device comprises a capsule 3 part-filled with a conductive liquid. The capsule is constructed to compensate for thermal effects, by forming the sides of the capsule so that they are responsive to internal pressure change caused by thermal expansion of the contents to expand the volume of the capsule to keep the level of liquid therein constant. First to fourth semi-circular electrodes A–D are disposed within the capsule in contact with the liquid. An electrical signal is applied between electrodes C, D (forming a common electrode) and first one and then the other of electrodes A, B, to derive a signal indicative of the degree of immersion of the electrode A, and then of the electrode B. The ratio of these signals is related to the angle of inclination of the capsule about the reference axis O and relative to a first reference angle defined at the gap 8 between the electrodes A, B. A similar gap 10 defining a second reference angle is disposed between

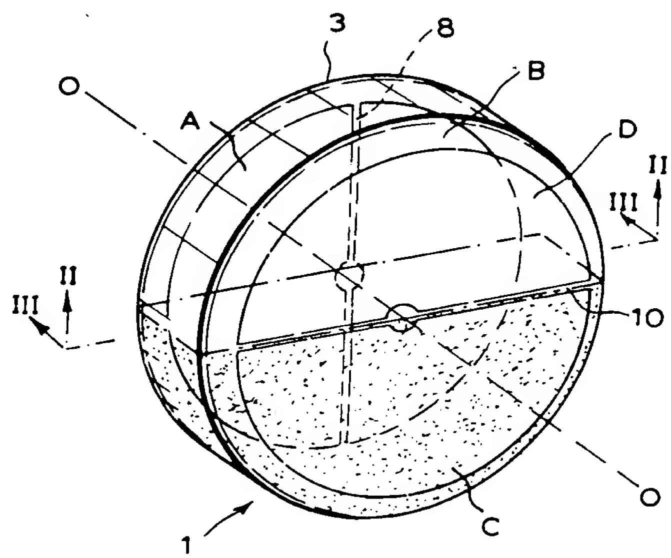

FIG.1.

Continued overleaf . . .

The claims were filed later than the filing date within the period prescribed by Rule 25(1) of the Patents Rules 1982.

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electrodes C, D, perpendicular to the gap between electrodes A, B, and by reconfiguring the electrodes A–D, to measure the degree of immersion of electrodes C and D, the sensor is able to sense any angle of inclination about the reference axis.

For use in an inclinometer, the capsule is inserted in a mount (19, Fig. 4 not shown) with a straight edge (21).

Measuring circuitry is described and a sample calculation is given for the capsule dimensions. The described capsule consists of polybutylene terephthalate mouldings reinforced with 15–20% glass beads, with a water-methanol mixture as conducting liquid.

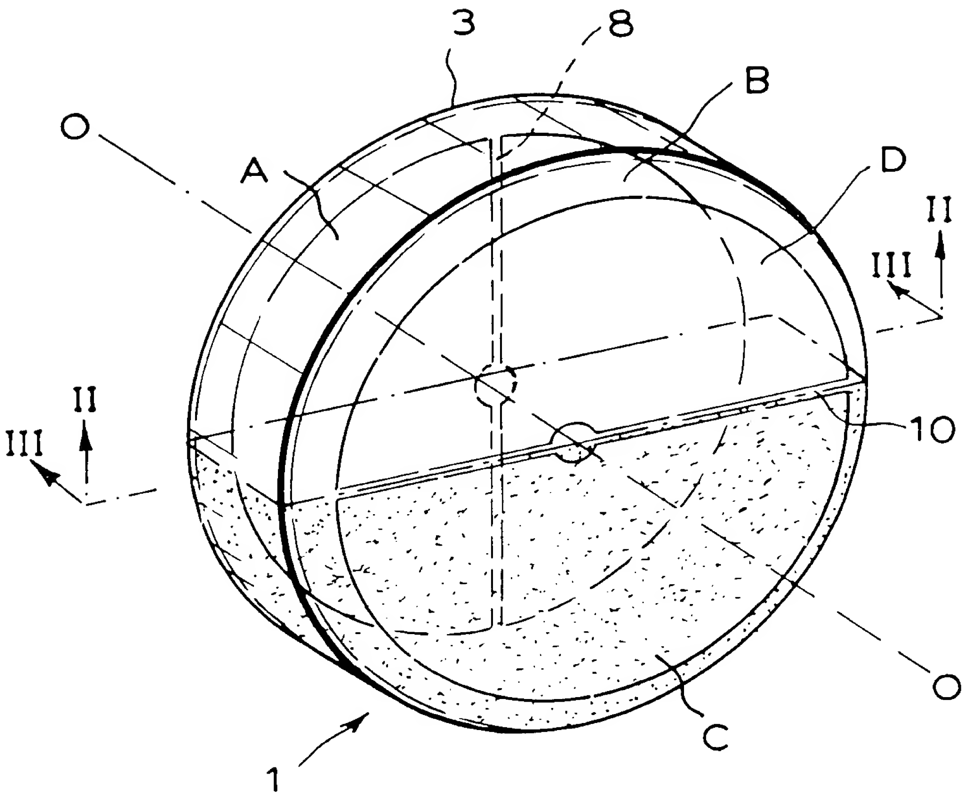

FIG.1 .

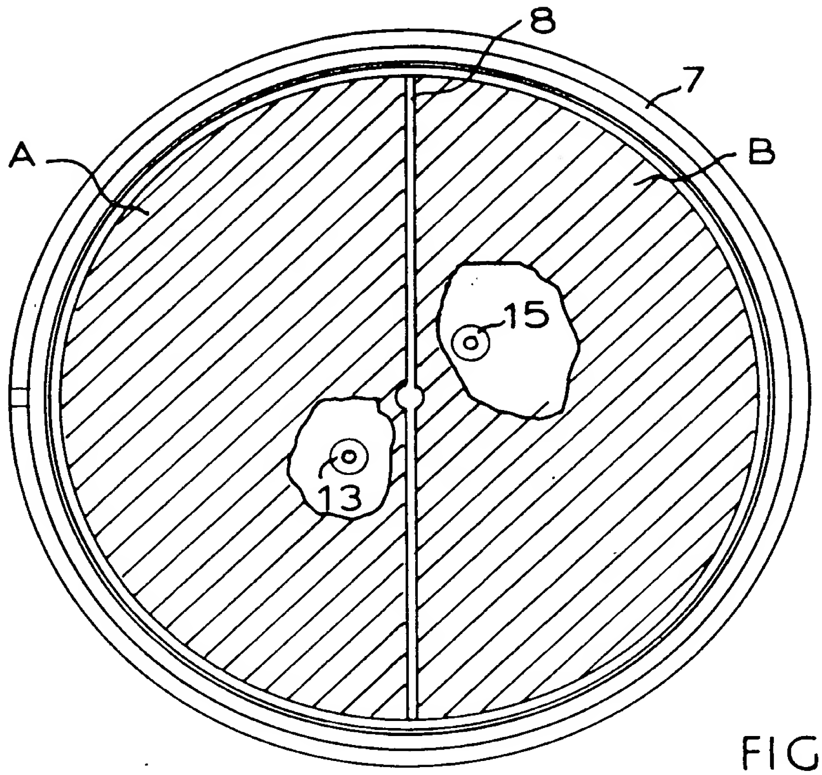

FIG. 2.

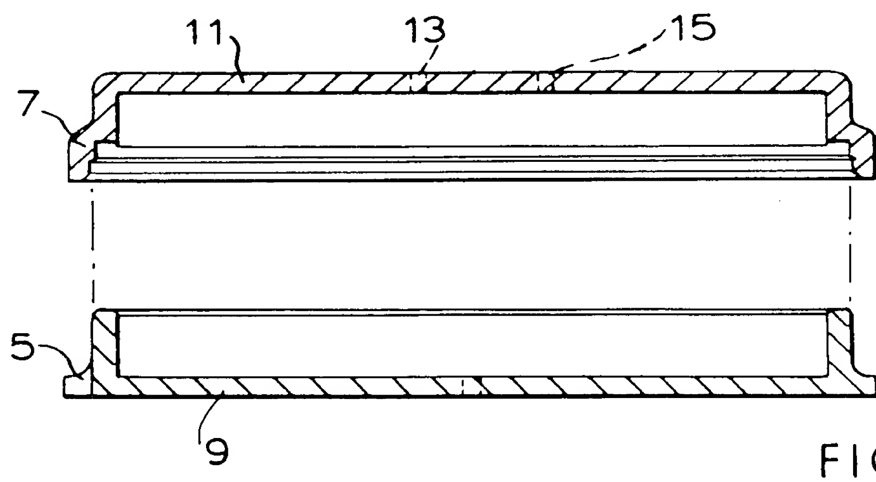

FIG. 3.

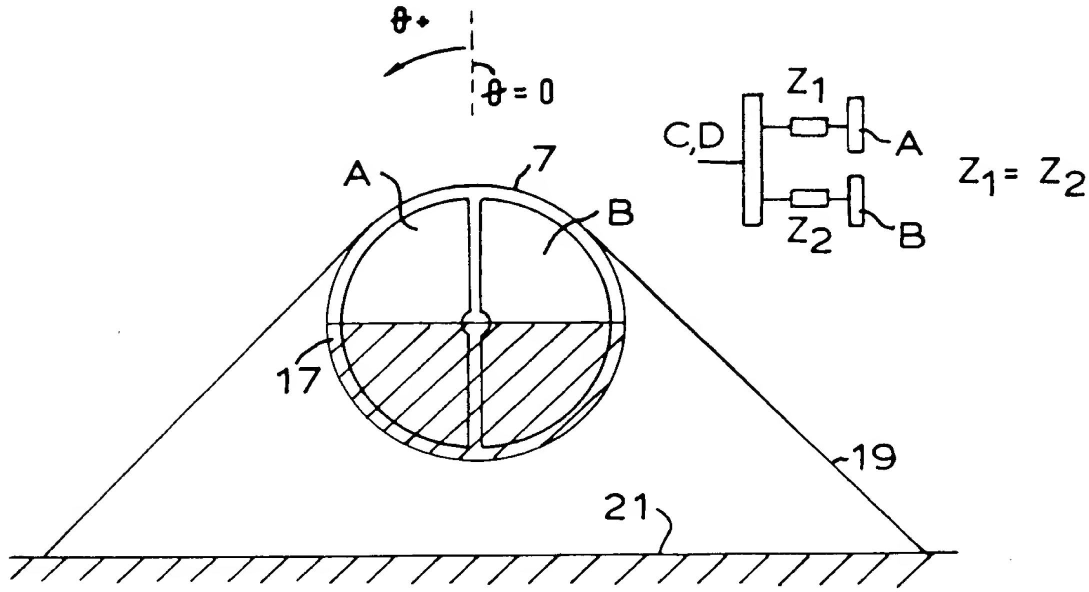

FIG. 4a.

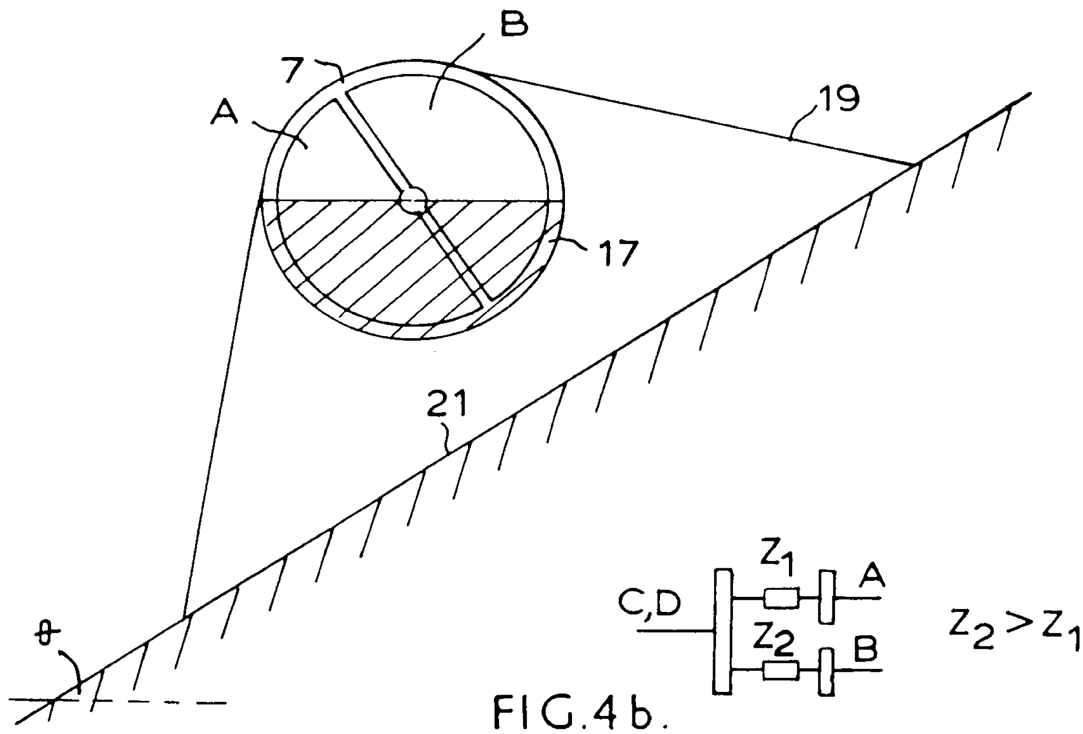

FIG. 4b.

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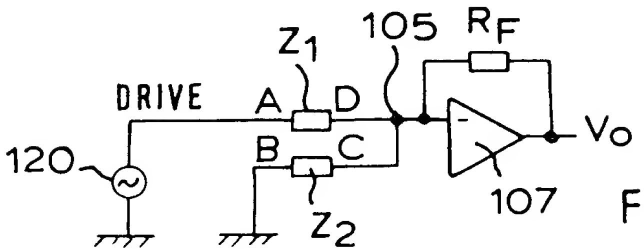

FIG.5a.

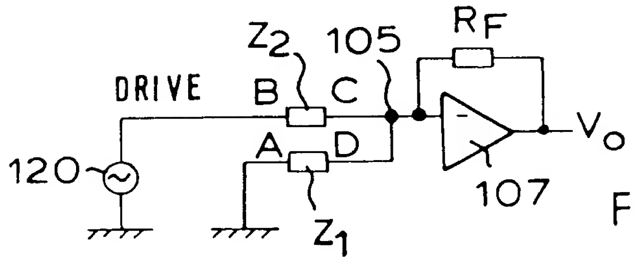

FIG.5b.

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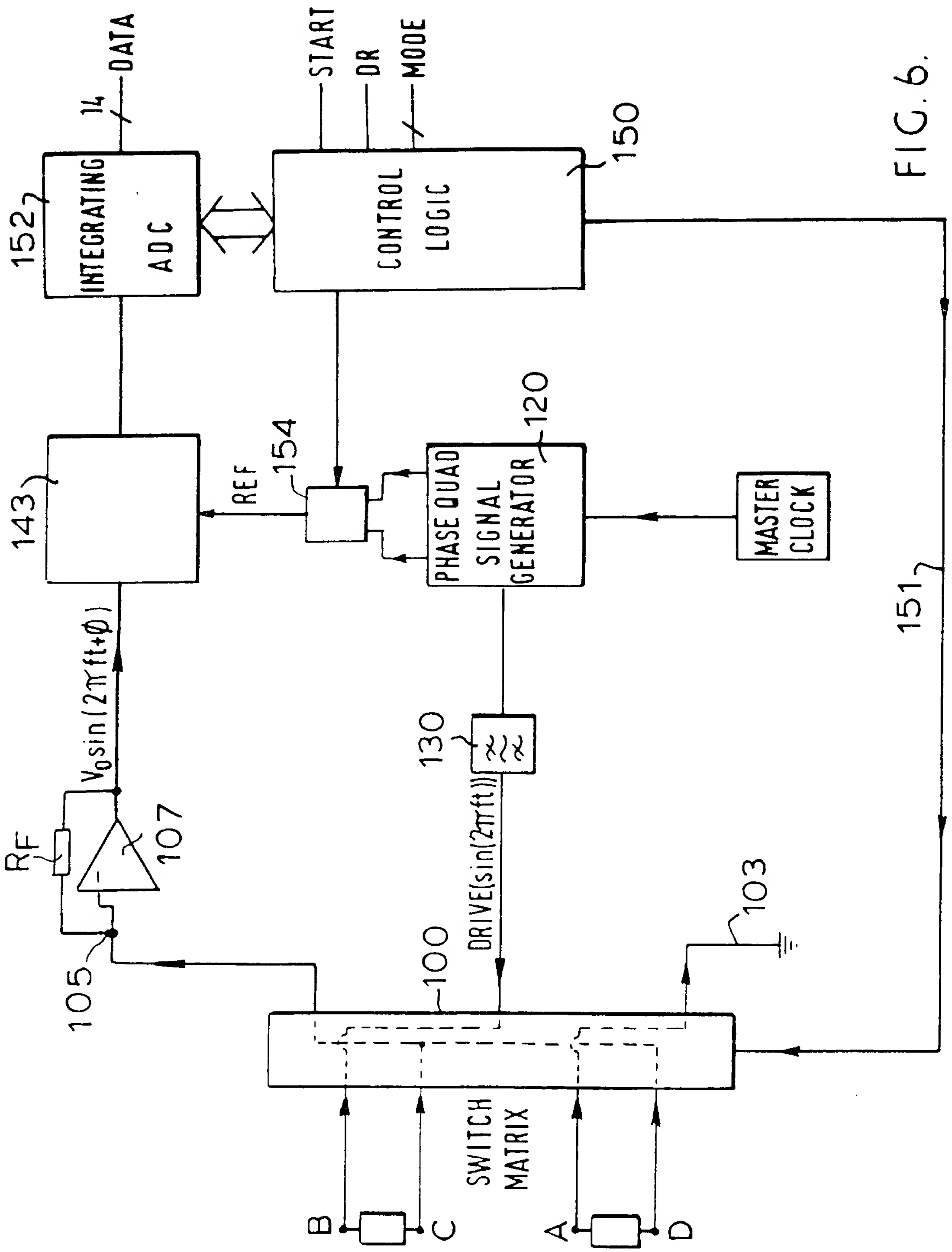

FIG. 6.

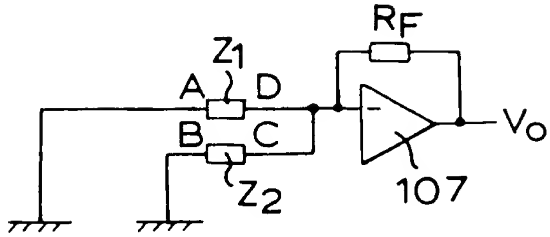

FIG. 7.

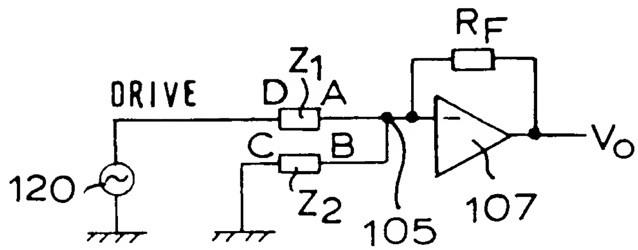

FIG. 8a.

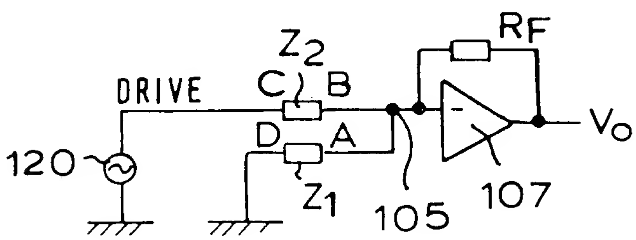

FIG. 8b.

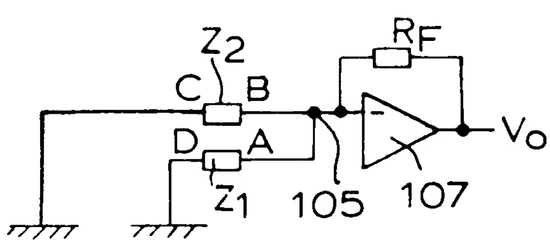

FIG. 8c.

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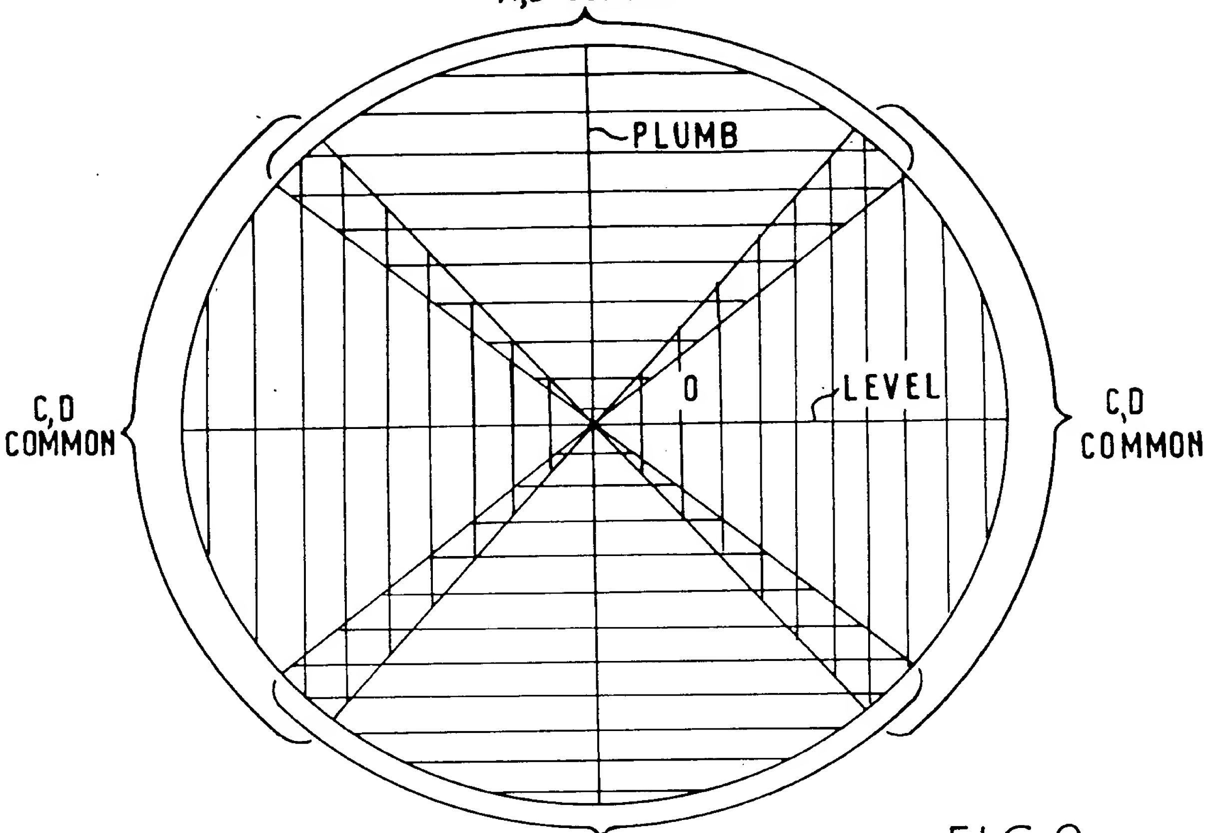


FIG.9.

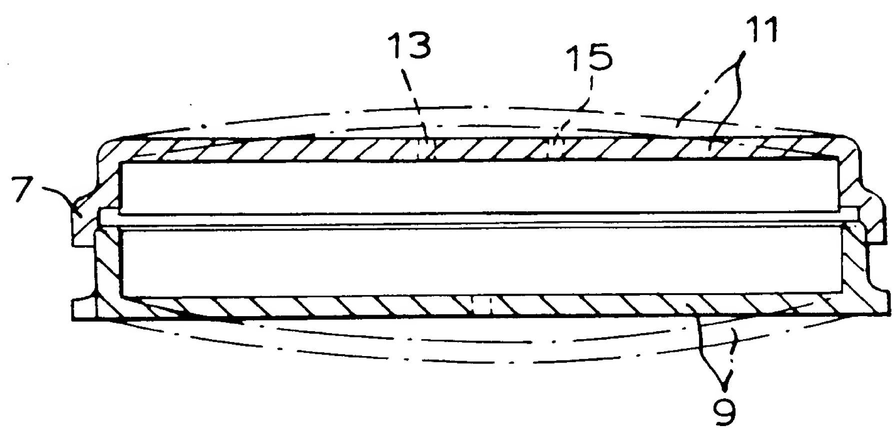


FIG.10.

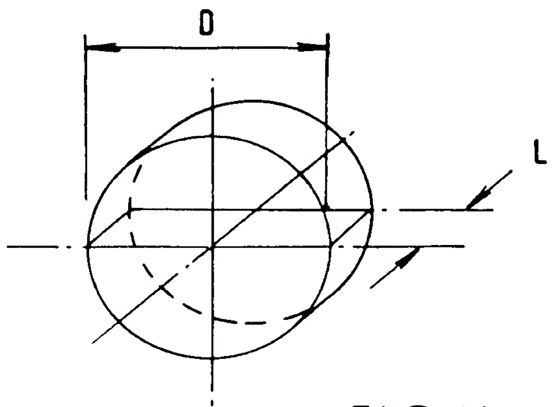
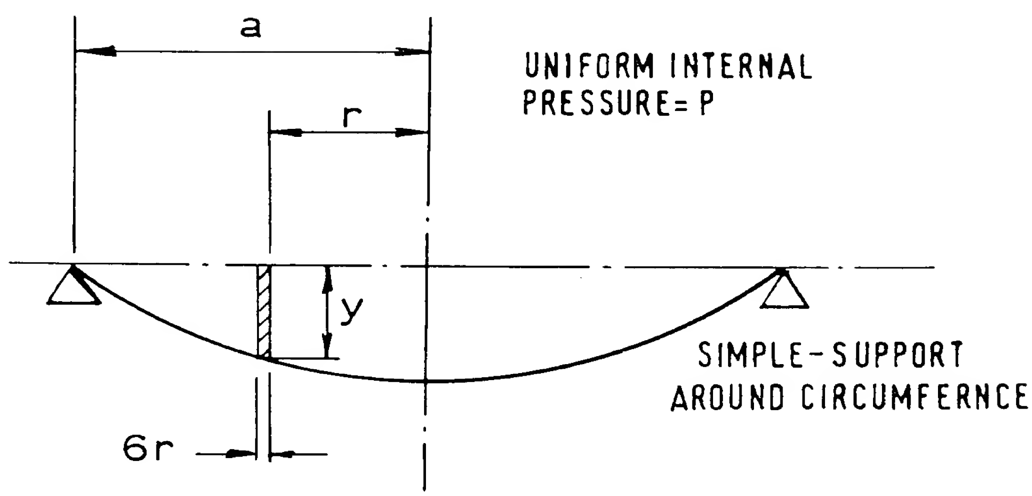


FIG.11.



<u>NOTATION FOR GEOMETRY OF FLAT CIRCULAR PLATE UNDER UNIFORM PRESSURE</u>
(DEFLECTION EXAGGERATED FOR CLARITY)

FIG.12.

SPECIFICATION

A device

This invention relates to a device and, more particularly, but not exclusively to a sensor for an electronic level of inclination gauge.

Optical levels, more commonly called spirit levels, are well known and provide an optical indication of whether or not a surface is horizontal, based in the principle of an air bubble in a liquid-filled vial always seeking the highest point in the vial, the vial being slightly curved so that when at level, the bubble will always take up an equilibrium position. Such bubble levels, if disposed in a suitable frame, can also be used to provide an indication of whether or not a surface is vertical.

However, such spirit levels are not capable of measuring deviations from horizontal or vertical outside a very limited range. Also, such spirit levels can be difficult to read accurately as the measurement of level or plumb depends on the ability of the user to determine the position of the bubble. Factors such as poor lighting or poor eyesight obviously affect this.

An electronic spirit level has been proposed by Cantarella, in U.S. 4 167 818, which uses a capsule part-filled with a conductive liquid. Several electrodes are disposed within the capsule, the resistance between the electrodes being dependent on the position of the liquid within the capsule which, in turn, is dependent upon its inclination. A digital readout of angles of inclination from level and from plumb is provided. However, this level, again, is only usable over a limited range of angular deviation from horizontal or vertical. Also, the accuracy of any measurement from horizontal or vertical is dependent upon ambient conditions such as temperature, as fluctuations in temperature will lead to variations in the level of liquid within the capsule which in turn will affect the reading of inclination for angles for which the electrodes are not equally immersed in the liquid.

Capacitive devices, such as that disclosed in EP 35840 have also been proposed. The device of EP 35840 includes a capsule of generally cylindrical form part-filled with a liquid having a dielectric constant different from that of the remainder of the capsule. The capsule is provided with four electrodes, a single, primary, electrode bing disposed on one end surface of the capsule and the three other, secondary, electrodes being disposed on the other end surface. Three sensing circuits including three oscillators are provided for sensing the capacitance between the first electrode and the three secondary electrodes.

However, it is believed that this device is also prone to fluctuations due to temperature changes, due to the changing dielectric constant of the liquid used which affects the measurement of inclination and needs to be compensated for by the processing circuitry. Also, the three secondary electrodes each need a separate processing circuit. As each processing circuit tends to have its own individual characteristics, it is believed that compensation for this is also necessary. These factors lead to additional manufacturing expense.

According to the invention in a first aspect, there is provided a capsule, part-filled with a liquid, the walls of the capsule having a different coefficient of thermal expansion from the liquid and being formed so that a temperature-induced pressure change within the capsule will cause the walls of the capsule to deform elastically to maintain the level of the liquid in the capsule substantially constant.

According to the invention in a second aspect, there is provided a sensor comprising a sealed capsule part-filled with a liquid and provided with first and second electrode means in contact with the liquid, the impedance between the first and second electrode means being dependent upon the angle of inclination of the capsule and the walls of the capsule being elastically deformable in response to pressure within the capsule to allow the volume of the capsule to change in response to said pressure so that the level of liquid in the capsule is maintained substantially constant.

According to the invention in a third aspect there is provided an electronic level or inclination gauge comprising a capsule part-filled with a conductive liquid, first and second electrode means, disposed within the capsule for contact with the liquid, a sensing circuit for sensing, sequentially, a plurality of electrical quantities together indicative of the angle of rotation of the capsule about a reference axis and switching means for connecting said electrode means to the sensing circuit and to an excitation source in a plurality of configurations for measuring said electrical quanties.

According to the invention in a fourth aspect there is provided a sensor for an electronic level of inclination gauge, the sensor comprising a capsule part-filled with a conductive liquid,

first and second spaced electrode means disposed within the capsule

each said electrode means comprising first and second like electrodes disposed about a reference axis and being electrically separated one from another so that, for any angle of rotation of the sensor about the reference axis, at least three of said electrodes are in contact with the liquid.

An embodiment of the invention will now be described, by way of example, with reference to

the accompanying drawings, in which:

Figure 1 is a perspective view of a sensor capsule forming part of an embodiment of the invention;

Figure 2 is a sectional view taken in the plane II–II′ of Fig. 1;

Figure 3 is an exploded sectional view taken through the plane III–III′ of Fig. 1;

Figures 4A–B are sectional views similar to Fig. 2 of the capsule at different inclinations;

Figures 5A and 5B show basic configurations of the sensing circuitry for the capsule shown in Figs. 1 to 4;

Figure 6 is a block diagram of the general arrangement of the sensing circuitry;

Figure 7 shows a null measurement arrangement of the circuit shown in Fig. 5;

Figure 8 shows alternative arrangements of the sensing circuitry shown in Figs. 5 to 7 for use in measuring an alternative range of angles;

Figure 9 illustrates the angular range of the sensor.

Figure 10 illustrates the ability of the capsule shown in Figs. 1 to 3 to compensate for temperature fluctuations.

Figures 11 and 12 are diagrams illustrating features of the design calculations for calculating a preferred capsule wall thickness, for temperature compensation purposes.

Referring to Figs. 1 to 3, an inclination sensor, generally designated 1 is shown. The sensor comprises a capsule 3 of generally cylindrical form. The capsule 3 is formed from two engageable non-conductive chemically inert plastics mouldings 5, 7 formed preferably from thermoplastic polyester (e.g. a polybutylene terephthalate (PBT) for example VALOX) (R.T.M.) reinforced with 15–20% glass beads to provide strength and stability. The mouldings 5, 7 are ultrasonically welded together to ensure a hermetic seal. The end faces 9, 11 of the mouldings 5, 7 are formed of a thickness so as to be elastically deformable in response to pressure variations within the capsule 3, as described hereinafter.

Within mouldings 5, 7, electrodes A, B and C, C formed from nickel are respectively disposed. Each electrode A–D is of generally semi-circular form and is formed on its respective mouldings 5, 7 preferably by vacuum deposition or hot foil blocking (although it is to be appreciated that other electrode-forming methods may be employed). The electrodes A, B (or C, D) are separated one from the other by an elongate gap 8 (or 10) so that the electrodes A, B or C, D are not in direct electrical contact. The gaps 8, 10 should be narrow, preferably less than 0.5 mm. Connections to the electrodes A–D are provided by means of rivets formed from conductive plastics material, which are bonded, preferably by ultra-sonically welding to the case halves; rivets 13, 15 for electrodes A, B are shown in Fig. 2.

The electrodes A, B are rotated by 90° about a reference axis O of the capsule with respect to the electrodes C, D to allow measurement of angles through 360° as described hereinafter. A conductive liquid 17 is disposed within the capsule 3, preferably a mixture of distilled water and methanol, the capsule 3 being filled, at NTP to half its volume. The remainder of the capsule is filled with air or an inert gas.

The general mode of operation of the capsule is described with reference to Figs. 4A and 4B for which a measurement using electrodes A, B as the sensing electrodes is illustrated. Figs. 4A and 4B illustrate the capsule 3 in a schematically shown mounting 19 having an edge 21 which is presented to a surface, the inclination of which is to be measured. One pair of electrodes in this case C, D are coupled together to form a common electrode and an alternating voltage is applied in turn to the electrodes A or B. The impedance and, more particularly, the resistance of the path between electrodes C, D and electrode A or electrode B is dependent upon the degree of immersion of electrode A or electrode B in the conductive liquid 17, the larger degree of immersion, the lower the resistance of the path.

Thus by measuring the resistance of the two paths, between electrodes C, D and electrode A and electrodes C, D and electrode B, the angle of inclination θ of the sensor can be calculated.

More specifically as can be seen by comparison of Figs. 4A and 4B, the total wetted area of electrodes A, B is always substantially a constant, so that, ignoring cross impedances:

$$\frac{1}{Z_T}=\frac{1}{Z_1}+\frac{1}{Z_2} \qquad 1a$$

where

Z_T = The total resistance of the capsule
Z_1 = The resistance of path CD to A
Z_2 = The resistance of path CD to B

and

$$Z_1 = \frac{180}{90+\theta} \cdot Z_T \qquad 1b$$

$$Z_2 = \frac{180}{90-\theta} \cdot Z_T \qquad 1c$$

So, the ratio, R, of the resistances Z1, Z2 is:

$$\frac{Z_1}{Z_2} = R = \frac{90-\theta}{90+\theta} \qquad 2$$

hence

$$\theta = \frac{90\ (1-R)}{(1+R)} \qquad 3$$

Exemplary values of R are as follows:

TABLE 1

θ	$R = \frac{Z_1}{Z_2}$
- 90	∞
- 50	3.5
- 45	3
0	1
+ 45	0.33
+ 50	0.286
90	0

Circuitry for measuring the resistances Z_1, Z_2 will now be described with reference to Fig. 5 which shows an operational amplifier 107 in an inverting mode, with feedback resistor R_F being connected between the inverting input terminal and output terminal of the amplifier 107.

Terminals C, D are commoned together and connected to terminal 105 of OP-amp 107; in Fig. 5A, terminal A is connected to A.C. source 120 while terminal B is connected to ground, with these terminals being swapped in Fig. 5B.

Referring to Fig. 5A, assuming $V_{IN} = 1$ volt

$$V_{01} = \frac{-A\ R_F Z_2}{A\ Z_1 Z_2 + Z_1 R_F + Z_1 Z_2 + Z_2 R_F} \qquad 4$$

and in Fig. 5B,

$$V_{02} = \frac{-A\ R_F Z_1}{A\ Z_2 Z_1 + Z_2 R_F + Z_2 Z_1 + Z_1 R_F} \qquad 5$$

. . . where A is the open loop gain of the operational amplifier 107.

combining 4 and 5:

$$R = \frac{Z_1}{Z_2} = \frac{V_{02}}{V_{01}} \qquad 6$$

... V_{01}, V_{02}, V_{IN} being peak amplitudes.
... so that switching of terminals A, B will give a measurement of V_{01} and V_{02} from which R can be calculated which, by Equation 3, will give θ.

A circuit for generating a digital value corresponding to each of these variables is shown in Fig. 6 and includes a switch matrix 100 connected to electrodes A–D the matrix having further connections to: an input terminal having a drive input waveform applied from signal generator 120 via band pass filter 130 of the form sin ($2\Pi ft$) (t=time (secs): f=frequency (Hertz)), an earth connection 103 and an output terminal connected to operational amplifier 107. The switching functions of the matrix 100 are controlled by control logic circuitry 150 via control bus 151. Electrode configuration instructions are sent to the control logic from computing circuitry (not shown) via the MODE lines. Connections equivalent to that illustrated in Fig. 5b are shown in phantom lines.

The output from operational amplifier 107 is fed to a multiplier 143. The multiplier 143 is connected to an integrating analog to digital converter 152 which integrates the output of the multiplier and converts the integrated signal into a 14 bit digital signal, which is output to computing circuitry (not shown) for calculation of the inclination angle.

The multiplier 143 is also supplied with reference signals from the signal generator 120. The reference signals comprise two outputs (Phase and Quad) of the same frequency as the drive waveform and in phase quadrature with one another (sin($2\Pi ft$), cos($2\Pi ft$)). Phase and Quad need not be in phase with the drive signal. These signals are alternatively supplied to the multiplier 143 through a switch 154 controlled by control logic unit 150.

The multiplier acts to multiply the waveform input from amplifier 107 (generally of the form A sin ($2\Pi ft+\phi$)) by the chosen reference signal so that its output is, sequentially:

$$V_0 \sin(2\pi ft+\phi).\sin(2\pi ft) \qquad 12a$$
$$V_0 \sin(2\pi ft+\phi).\cos(2\pi ft) \qquad 12b$$

The signals represented by equations 12A and 12B are integrated over N cycles of the signal waveform (N being an integer) with respect to time by integrator 152, giving:

$$\int_N V_0 \sin(2\pi ft+\phi).\sin 2\pi ft = KV_0 \cos\phi \qquad 13a$$

$$\int_N V_0 \sin(2\pi ft+\phi).\cos 2\pi ft = KV_0 \sin\phi \qquad 13b$$

K=constant

The circuit provides a 14 bit output proportional to these values. As can be seen, squaring 13A and 13B and adding gives:

$$K^2V_0^2 \cos^2\phi + K^2V_0^2 \sin^2\phi = K^2V_0^2 \qquad 14$$

... which is proportional to V_0^2 and thus proportional to the amplitude of the signal input to multiplier 143.

The multiplier may be replaced by logic, which gates the input signal from op amp 107 with a reference signal which pulses on, then off, at half cycle intervals of the drive signal sin ($2\Pi ft$). Gating the input signal in this way has the same effect as multiplying the input signal by sinusoidal signal of the same frequency as the device signal provided that the input signal is substantially free from harmonics and D.C. terms.

Gating the input signal, alternatively, with two such reference signals in phase quadrature will then provide the two ouputs of equations 12a and b.

In an alternative configuration, a single reference signal (sin $2\Pi ft$) which is in phase with the drive signal (sin $2\Pi ft$) may be applied to multiplier 143. The resulting multiplied output will then only contain components of the waveform input from Op Amp 107 which are independent of the arbitrary phase Φ (effectively $\Phi=0$ for this measurement) so that, with reference to equation 13a, the integrated output will be $KV_0 \cos 0 = KV_o$, so a quadrature measurement is unnecessary.

In order to compensate for DC offsets present in the circuitry, the control logic is also operable in a calibration (NULL) mode, for measuring of the DC offset prior to each resistance

measurement. For this, the circuitry is configured as shown in Fig. 7, with terminals A, B both being connected to ground and the offset V_{01n} (or V_{02n} which is equivalent to V_{01n}) being measured as appropriate.

In all, the following sequence of events (initiated in response to a start signal (START) from the computing circuitry) is required for one inclination measurement to be made:

Table 2

Measurement		Measured quantity
NULL		V_{01N}
Z_1	Phase	$V_{01P} + V_{01N}$
Z_1	Quad	$V_{01Q} + V_{01N}$
NULL		V_{01N}
Z_2	Phase	$V_{02P} + V_{02N}$
Z_2	Quad	$V_{02Q} + V_{02N}$

Alternatively, if the drive and reference signals are in phase, as previously described, only the measurement of Z_1 phase and Z_2 phase are necessary.

When a measurement is finished, the control logic sends a signal to the computing circuitry by means of the data ready (DR) line.

Electrodes A, B are used for sensing angles up to $\pm 50°$ from the horizontal in the configuration illustrated in Figs. 4A and 4B. For angles of inclination greater than these limits, the control logic reconfigures the electrodes so that the electrodes A, B become the common electrode and the orthogonally disposed electrodes C, D become the sensing electrodes, the sensor measuring angles in this configuration in the range $\pm 50°$ from vertical. The electrode configuration for these measurements, together with the offset configuration are shown in Fig. 8A–C. The sequence of events for the measurement of inclination for the electrodes in this configuration is analogous to that previously described with reference to Table 2.

Use of such electrode switching allows a full 360° of inclination angle to be measured, in terms of deviation from level or plumb, (as shown in Fig. 9) with the electrode configuration being chosen by the computing and control circuitry in accordance with the angle of inclination of the sensor. When initialising an inclination measurement, the processing circuitry performs a measurement with an arbitrary pair of electrodes e.g. C, D chosen as the common pair as shown in Figs. 5a, 5b and 7. If the ratio R calculated by the computing circuitry is within an allowable range ($\pm 50°$) (see Table 1), the measurement proceeds whereas if the measured ratio is outside the allowable range, the configuration is changed to that shown in Fig. 8 and the measurement is then performed.

As previously mentioned, the DC offset level of the circuit is tested before each measurement. The reason for the frequency of this testing is that the DC offset level fluctuates with temperature.

The volume of the liquid 17 within the capsule 3 is also prone to fluctuation with temperature. Due to the different coefficients of thermal expansion of the capsule and the liquid, changes in temperature will result in changes in liquid level which will affect the measurement of inclination. In order to compensate for this, the sides 9, 11 of the capsule moulding 5, 7 are chosen to be of a thickness so as to be elastically deformable in response to change in pressure caused by change in volume of the liquid and change in gas vapour pressure within capsule 3 due to change in temperature as illustrated in Fig. 10 (for an increase in temperature). For a certain side thickness, the deformation of the sides 5, 7 will increase the volume of capsule 3 to match the increased volume of the liquid so as to keep the level of liquid 17 substantially constant, as illustrated by the following exemplary design calculations:

A method for providing intrinsic thermal compensation of liquid level within a cylindrical capsule
ASSUMPTIONS

1) That it is necessary to prevent (or reduce to negligible proportions) the variation in liquid

level with temperature, within an hermetically sealed, part-filled, cylindrical vessel. (NB. the principle may be extended to non-cylindrical vessels).

2) That the liquid has a bulk coefficient of thermal expansion which is positive, and significantly greater than that of the vessel.

3) That the gas or vapour filling the remainder of the vessel displays a thermal variation of pressure which is essentially linear over the working temperature range.

4) That the vessel material is homogeneous, isotropic and has a single, positive value of thermal expansivity.

(NB. The principle may still be employed if this assumption is not met, but the design calculations would become more involved).

5) For this particular design, the cylindrical vessel is mounted with the axis horizontal. The vessel walls are thin in relation to the vessel size and are not stressed beyond the elastic limit. All deflections are small.

DESIGN CALCULATIONS

1) Differential thermal expansion

Consider a cylindrical vessel of diameter D, of unit axial length and filled to a diameter with liquid of bulk thermal expansion coefficients e_f. The vessel is made of material having a linear expansion coefficient of e_v, as illustrated in Fig. 11.

The linear expansion coefficient is defined such that at temperature $T+\delta T$,

$$\text{diameter} = D(1+e_v\delta T)$$

and the bulk coefficient of the liquid similarly:

$$\text{volume} = V(1+e_f\delta T)$$

where V = initial volume at temperature T.

Now vessel volume at T

$$= \frac{\pi . D^2}{4}$$

new volume at $T+\delta T$

$$= \frac{\pi}{4}[D(1+e_v\delta T)]^2\ (1+e_v\delta T)$$

$$= \frac{\Pi D^2}{4}(1+e_v\delta T)^3 \qquad (1)$$

Original liquid volume at T

$$= \frac{\pi D^2}{8}$$

$$\text{New liquid volume} = \frac{\pi D^2}{8}(1+e_f\delta T)$$

∴ liquid rises in vessel by a height given by:—

$$\frac{\text{new liquid volume} - 1/2 \text{ of new vessel volume}}{\text{new X-sectional area of diameter}}$$

(NB. This assumes that variations in liquid level are small).

∴ liquid level rise

$$= \frac{\frac{\pi D^2}{8}(1+e_f\delta T) - \frac{\pi D^2}{8}(1+e_v\delta T)^3}{D.\ (1+e_v\delta T)^2}$$

$$= \frac{\frac{\pi D}{8}[1+e_f\delta T-(1+e_v\delta T)^3]}{(1+e_v\delta T)^2}$$

expanding, and neglecting powers of e_f and e_v,

$$= \frac{\frac{\Pi D}{8}[e_f\delta T - 3e_v\delta T]}{1+2\ e_v\delta T} \qquad (2)$$

which is approximately:

$$\frac{\pi D}{8}\delta T\ (e_f - 3e_v) \qquad (3)$$

(since $2.e_v\delta T <<< 1$)
Note that $3.e_v$ = bulk expansion coefficient of the vessel.

2) Vessel bulging due to internal pressure

For a flat, circular plate, simply-supported at the circumference, the deflection at any point at radius r from the centre, is given by:—

$$y = \frac{3.\ P\ a^2\ (1-V^2)}{8\ E\ t^3}\left[\frac{(5+v)a^2}{2(1+v)} + \frac{r^4}{2a^2} - \frac{(3+v)r^2}{(1+v)}\right] \qquad (4)$$

(REF ROARK. Formulas for stress and strain (McGraw Hill, 4th Edition) Page 216, Case 1)

where P = internal pressure
a = radius of plate
E = Youngs modulus of plate material
t = plate thickness
V = poissons ration of plate material
(assumes material is isotropic)

The incremental volue due to this deflection is given by:—

$$2\pi \int_{r=o}^{r=a} y.r.dr \qquad (5)$$

(See Fig. 12)

Assuming that pressure/temperature is given by the gas laws:—

$$\frac{P_2}{P_1} = \frac{T_2}{T_1}$$

or $P_2 = P_1\frac{T_2}{T_1}$

or $P=P_2-P_1$

$$=P_1\frac{(T_2-1)}{T_1}$$

$$\simeq\frac{1}{293}P_1/K \text{ (for small temperature changes}$$

(Assuming that $T_1=20°C=293K$)

∴ bulge volume, as a function of temperature is given by:—

$$\frac{2\pi}{293}\,\frac{3}{8}\,\frac{P_1\,a^2\,(1-v^2)}{E.\,t^3}\int_{r=o}^{r=a}\left[\frac{(5+v)}{2(1+v)}a^2+\frac{r^4}{2a^2}-\frac{(3-v)r^2}{(1+v)}\right]r.dr \quad (mm^3/K)$$

Substituting values:—

$p_1=0.1\ N/mm^2$ (=1 bar)
$a=25$ nm
$v\simeq0.4$ (for polyester. ref KEMPE'S.
$E\simeq2300\ N/mm^2$ (for VALOX material nominal value)

and integrating gives:—

$$\frac{2\pi}{293}\,\frac{3}{8}\,\frac{0.1\ 25^2\ .0.84}{2300\ t^3}\int_0^{25} 1250r+\frac{r^5}{1250}-2.429r^3\ dr.$$

$$=\frac{183.559}{10^6t3}\left[\frac{1205r^2}{2}+\frac{r^6}{7500}-\frac{r^4}{1.6468}\right]_0^{25}$$

$$=\frac{31.56}{t^3}mm^3/K \qquad (6)$$

3) Equate thermal expansion to vessel bulging.
Taking expansivity values of exemplary materials used:

For methanol: $e_f=1190\ .10^6$ (BULK)
For VALOX: $e_v=\ 70\ .10^6$ (LINEAR)
(nominal value)

Differential volume change due to thermal expansion

=liquid height change × diametral cross-section

$$=\frac{\pi.D}{8}(1190-3.70)\ .10^{\ 6}\ .D.L \text{ (from (3))}$$

where L=axial length of vessel=10 mm.

$$= \frac{\pi.50^2\ .10}{8.10^6}(1190-210)$$

$$= \frac{9.621\ mm^3/K}{}$$

$$9.621 = \frac{31.56}{t^3}$$

$$t^3 = \frac{31.56}{9.621}$$

$$t = \frac{1.486\ mm}{}$$

NOTE This assumes that there is negligible pressure bulging of the *cylindrical* wall of the vessel and that both circular walls are of equal thickness.

The principle can still be employed if these assumptions are not met.

For ease of calculation, it has been assumed that the capsule walls are simply-supported at the circumference and of uniform thickness. More refined analysis can be carried out within the ability of one skilled in the art by, for example, finite element techniques to provide a more accurate determination of equation 6 for a particular application.

It is to be appreciated that this principle is usable in applications other than for the inclination sensor described.

CLAIMS

1. A capsule, part filled with a liquid, the walls of the capsule having a different coefficient of thermal expansion from the liquid and being formed so that a temperature-induced pressure change within the capsule will cause the walls of the capsule to deform elastically to maintain the level of the liquid in the capsule substantially constant.

2. A capsule as claimed in claim 1 wherein the capsule is formed as a hollow cylinder, the end walls of the cylinder being arranged to deform in response to said pressure change and the cylindrical side wall of the cylinder being arranged to be irresponsive to said change.

3. A capsule as claimed in claim 1 or claim 2 wherein the capsule is formed from plastics material.

4. A capsule as claimed in claim 3 wherein the plastics material is a polybutylene terephthalate.

5. A capsule as claimed in claim 3 or claim 4 wherein the plastics materials is reinforced with glass beads.

6. A capsule as claimed in any one of the preceding claims wherein the liquid comprises methanol.

7. A capsule as claimed in any one of the preceding claims wherein the capsule comprises first and second mouldings connected together.

8. An inclination sensor including a capsule as claimed in any one of the preceding claims.

9. A sensor as claimed in claim 8 wherein the capsule further includes a plurality of electrodes arranged for contact with the liquid.

10. A sensor as claimed in claim 9 wherein said plurality of electrodes includes first and second electrodes disposed within the capsule, the relative degree of immersion of the first and second electrodes in the liquid being indicative, within a first angular range, of the angle of inclination of the capsule both about a reference axis and relative to a first reference angle.

11. A sensor as claimed in claim 10 wherein said plurality of electrodes further includes third and fourth electrodes disposed within the capsule, the relative degree of immersion of the third and fourth electrodes in the liquid being indicative, within a second angular range, of the angle of inclination of the capsule both about a reference axis and relative to a second reference angle different from the first reference angle.

12. A sensor as claimed in claim 11 wherein the first and second reference angles are those at which the first and second electrodes or the third and fourth electrodes, respectively, are equally immersed in the liquid.

13. A sensor as claimed in claim 11 or claim 12 wherein the first to fourth electrodes are arranged so that any angle of inclination of the capsule about the reference axis is included within at least one of the first and second ranges.

14. A sensor as claimed in any one of claims 11 to 13 wherein the first and second reference angles are orthogonally disposed.

15. A sensor as claimed in any one of claims 10 to 14 wherein the first and second electrodes are of substantially semi-circular form and are spaced one from the other about the reference axis.

16. A sensor as claimed in any one of claims 11 to 14 wherein the third and fourth electrodes are of semi-circular form and are spaced one from the other about the reference axis.

17. An inclination measuring device including a sensor as claimed in any one of claims 8 to 16, the sensor being mounted relative to a measuring surface disposed parallel to the reference axis, so that inclination of the measuring surface results in corresponding inclination of the sensor capsule.

18. A sensor for an inclination measuring device comprising:

a capsule part-filled with a conductive liquid,

first electrode means comprising first and second electrodes disposed within the capsule, the relative degree of immersion of the first and second electrodes in the liquid being indicative, within a first angular range, of the angle of inclination of the capsule both about a reference axis and relative to a first reference angle,

second electode means comprising third and fourth electrodes disposed within the capsule, the relative degree of immersion of the third and fourth electrodes in the liquid being indicative, within a second angular range, of the angle of inclination of the capsule both about the reference axis and relative to a second reference angle different from the first reference angle; and

the first and second electrode means being arranged so that any angle of inclination of the capsule about the reference axis is included within at least one of the first and second ranges and the first and second reference angles are those at which the electrodes of the first and second electrode means, respectively, are equally immersed in the liquid.

19. A sensor as claimed in claim 18 wherein the first and second reference angles are orthogonally disposed.

20. A sensor as claimed in claim 18 or claim 19 wherein the first and second electrodes are of substantially semi-circular form and are spaced one from the other about the reference axis.

21. A sensor as claimed in any one of claims 18 to 20 wherein the third and fourth electrodes are of semi-circular form and are spaced one from the other about the reference axis.

22. An inclination measuring device including a sensor as claimed in any one of claims 18 to 21, the sensor being mounted relative to a measuring surface disposed parallel to the reference axis, so that inclination of the measuring surface results in corresponding inclination of the sensor capsule.

23. A device as claimed in claim 22 further comprising:

a drive source for generating a drive signal to be applied to the capsule,

processing means for processing an output signal from the capsule,

switch means, arranged to select any one of the electrodes and to connect the selected electrode to the drive source whereby the drive signal is applied to the capsule through the selected electrode, the drive signal being modified by the impedance of the liquid between the selected electrode and a common electrode to form the output signal, the impedance being dependent upon the degree of immersion of the selected electrode in the liquid, and

control means, for controlling the operation of the switch means.

24. A device as claimed in claim 23 wherein the switch means is arranged to configure the electrodes so that the electrodes of the electrode means which does not include the selected electrode are connected together to form the common electrode.

25. A device as claimed in claim 23 or claim 24 wherein the switch means is arranged to select one, then the other, of the electrodes of one said electrode means and said selected electrode and to connect the non-selected electrode of the electrode means to ground.

26. A device as claimed in claim 25 wherein the drive source generates an alternating current drive signal.

27. A device as claimed in claim 26 wherein the processing means comprises:

amplifier means for amplifying the output signal,

multiplier means, for multiplying the amplified signal, sequentially, by first and second reference signals, to generate first and second multiplied signals, the first and second reference signals including a component having the same frequency as the drive signal and the reference signals being in phase quadrature with one another: and

integrating means, for integrating each multiplied signal over a predetermined number of cycles of the multiplied signal to form first and second integrated signals; and

calculation means, responsive to the integrating means, for deriving the inclination angle from the integrated signals associated with the sequentially selected electrodes.

28. A device as claimed in claim 27 wherein the multiplier means gates the amplified signal in accordance with the reference signals which each pulse on then off at half cycle intervals of the drive signal.

29. A device as claimed in claim 26 wherein the processing means comprises:
amplifier means, for amplifying a said modified signal,
multiplier means for multiplying the amplified signal by a reference signal including a component in phase with the drive signal to form a multiplied signal; and
integrating means for integrating the output of the multiplier means over a predetermined number of cycles of the signal, to form an integrated signals; and
calculation means, responsive to the integrating means, for deriving the inclination angle from the integrated signals associated with the sequentially selected electrodes.

30. A device as claimed in claim 29 wherein the multiplier means gates the amplified signal with the reference signal, the reference signal pulsing on then off at half cycle intervals of the drive signal.

31. A device as claimed in any one of claims 27 to 30 wherein the measuring means further comprises an analog-to-digital converter, for converting the output of the integrating means into a digital signal.

32. A device as claimed in any one of claims 27 to 31 wherein the control means is responsive to the processing means to select the electrodes of the first or second electrode means so that the angle of inclination to be measured lies within the respective range of the first or second electrode means.

33. A device as claimed in any one of claims 24 to 31 wherein the switch means further configures the electrodes in a DC offset measuring configuration in which either the first and second or the third and fourth electrodes are connected together to form the common electrode and the common electrode is connected to the measuring means and the non-commonly connected electrodes are connected to ground.

34. A device as claimed in claim 32 wherein the switch means is arranged to be configured in the DC offset measuring configuration between every electrode selection.

35. A capsule substantially as hereinbefore described with reference to the accompanying drawings.

36. An inclination sensor substantially as hereinbefore described with reference to the accompanying drawings.

37. An inclination measuring device substantially as hereinbefore described with reference to the accompanying drawings.

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